Effects of Welding Speeds and Power Inputs on the Hardness Property of Type 304L Austenitic Stainless Steel Heat-Affected Zone (HAZ)

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Abstract

Effects of welding speed and power input on the hardness property of Type 304L Austenitic Stainless Steel (ASS) Heat-Affected Zone (HAZ) welded with Gas Tungsten Arc Welding (GTAW) process were studied. Consequently, chemical analysis of the as-received 304L ASS was carried out to determine its chemical composition using AR4 30 metal analyzer. Thereafter, the as-received 304L austenitic stainless steel plate was cut with hacksaw into sample of dimensions 70 mm length, 45 mm breadth and 8 mm thickness, and thirty samples were produced in all, then classified into A, B and C with each having equal number of ten samples. The classified samples were further cut into two equal halves with hacksaw and welded under a range welding variables to produce butt joint HAZ samples. The obtained HAZ samples and as-received sample were machined to hardness, tensile, and impact test specimens. Hardness, tensile and impact measurements were made using standard approaches. Instron universal testing machine of model-3369, Rockwell hardness (H_{RA}) and Charpy–V impact testers were used for tensile, hardness and impact toughness respectively. Specimens for microscopy studies were prepared from the (HAZ and as-received) samples by machining to appropriate dimensions, then etched in a solution of 1 ml HCl + 3ml HNO_3 + 1 ml glycerol and the microstructures were examined using metallurgical microscope-Model AXIA 1m with camera attached at a magnification of 400xx. Results obtained from the HAZ micrographs showed that the hardness property of the HAZ was influenced at varying degrees at the range of welding speeds and power inputs investigated. Microstructure of the HAZ was a mixture of austenite and ferrite, also variation in volume fraction and grain size of the phases was observed. In addition, chromium carbide formation and precipitation due to sensitization was seen at the grain boundaries. Optimum hardness property was obtained at fast welding speed of 9.5 m/min and 9.20 kW power input.

Keywords

Hardness; Gas Tungsten; Arc Welding; ASS; Metallographic Examination

Introduction

Selection of Type 304L Austenitic Stainless Steel (ASS) as material of choice for various engineering applications such as structural steel parts in metallurgical, mechanical, chemical, automobile and nuclear industries cannot be traced only to its good corrosion resistant and formability characteristics, but also to its good welding characteristics (Fowless et al., 2008). Previous research work have showed that 304L ASS can be successfully welded with different welding techniques among which are Shielded Metal Arc Welding (SMAW), Gas Tungsten Arc Welding (GTAW), Submerged Arc Welding (SAW), and Plasma Arc Welding (PAW) (Woel-Shyan, Fan-Tzeng, and Chi-Feng, 2005), (EL-Batahgy and Abdel-Monem, 1997) and (Ramazan and Huseyin, 2002). Despite its good weldability, failure of this material in service due to cracking tendencies in the Heat-Affected Zone (HAZ) has been reported (Gunaraj et al., 2002).

The HAZ is the area of base metals whose microstructures and properties are altered by welding or heat intensive cutting operations (Agarwal, 1992), and according to Woel-Shyan Lee et al., (2005) performance of the welded structures is usually limited by failure initiation within the HAZ of the base material, particularly within the coarse- grain region of the HAZ adjacent to the weld metal. During welding, the weld thermal cycle produces differently featured heat-affected zone (HAZ) microstructures,

the different phase microstructures correspond to different mechanical properties (Iordachescu et al., 2010), and if the microstructural changes in the HAZ are not controlled as a result of improper selection of welding variables, undesirable metallurgical structures may be produced, consequence of which may lead to loss of weld joint quality and eventual failure of material in service(Bipin and Tewari, 2010). Therefore, selecting suitable process is one primary means by which acceptable HAZ properties can be achieved. A number of studies have been carried out on microstructural and mechanical behavior of welded 304L ASS, particularly in the weld joints, while only limited information on microstructural and mechanical behavior in the HAZ is available, this is in spite of the criticality of HAZ to service performance of welded structures, and if the reliability of large-scale structures under varied loading conditions is ensured, fundamental understanding of the effects of welding variables on HAZ microstructural and mechanical properties is required. Therefore, effort was made in this work to study the effects of welding speed and power input at different ranges on the microstructures and hardness property in the HAZ of 304L ASS.

Materials and Equipment

The type 304L austenitic stainless steel plate sheet used for the work is of 8 mm thickness, and the welding electrode of diameter ϕ = 2.5 used for the production of the weldment is of specification AWS 308L. And the equipment used was AR 4 30 metal analyser, Welding machines with the following specifications: GTAW 500: Duty 60% with input capacity 24.7 KVA, GMAW 500: Duty 60% with input capacity 13.5KVA and SMAW 500: Duty 60% with input 32.7 KVA, Digital Rockwell hardness tester, instron universal testing machine-model 3369, Charpy-V impact testing machine, Metallurgical microscope with camera model-AXIA 1 m, spectrometric analyser, polishing machine, 115 mm diameter angle grinder, bench vice, power hacksaw, Files, Chipping hammer, Stainless wire brush, vernier caliper, and emery papers.

Methods

Chemical composition of the as-received 304L austenitic stainless steel plate was done by optical emission spectrometry using AR 4 30 metal analyzer and the result is shown in Table 1.

TABLE 1 CHEMICAL COMPOSITION OF THE AS-RECEIVED 304L AUSTENITIC STAINLESS STEEL PLATE SHEET

Element	% Wt
C	0.038
Si	0.649
S	0.05
P	0.051
Mn	1.859
Ni	8.079
Cr	18.403
Mo	0.319
V	0.075
Cu	0.871
Nb	0.104
Co	0.172
Al	0.027
Pb	0.013
Ca	0.005
Zn	0.031
Fe	69.65

Samples Preparation and Welding

The ASS plate was cut with hacksaw into samples of dimensions 70 mm length, 45 mm breadth and 8 mm thickness. A total of thirty samples was produced, then grouped into A and B, with each of the group containing equal number of ten (15) samples. Thereafter, samples of 50 mm length were marked out into square geometry and cut with hacksaw. One half of the samples was then joined to the corresponding ones at a range of welding speeds and power inputs to produce square geometry butt joint samples. The obtained butt joint samples as well as the as-received sample were machined to shapes with lathe machine to produce hardness specimens. Machining of the as-received sample was done longitudinally, while that of the welded samples was done across the HAZ of the weldments.

Hardness Test

Standard approaches and machines were used to measure hardness property of the machined specimens. Surfaces of the (as-received and HAZ) samples with dimensions 15 mm length, 10 mm breadth and 8 mm thickness were properly ground to give it flat and stable surface using a hand grinder (Fig. 1). Thereafter, hardness measurement was made using Digital Rockwell hardness (H_{RA}) Tester with 0.4064 m indenter and 0.6 N indenting load with a dwell time of 10 s. The hardness measurement was taken in three different locations and the average values were considered (Olaniran et al., 2007). The results are shown in Table 2.

TABLE 2 HARDNESS RESULTS OF THE SAMPLES

S/N	Sample condition	Varied Parameter	1ST	2ND	3RD	Average Hardness Value (HRA)
1	As received	-	48.6	49.6	47.0	48.4
2	Welded	Speed (m/min)				
		Fast (9.5 m/min)	42.3	48.7	51.2	47.4
		Moderate (4.5 m/min)	43.2	42.4	51.7	45.8
		Slow (2.5 m/min)	40.1	40.7	45.5	42.1
3	Welded	Power input (kW)				
		4.60	44.9	45.7	42.1	44.2
		9.20	49.2	48.9	44.6	47.5
		12.00	43.3	46.3	48.7	46.1

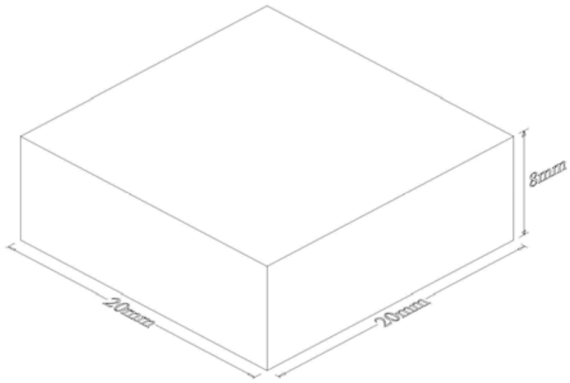

FIG. 1 HARDNESS TEST SPECIMEN

Metallography

Specimens for microscopy studies (as-received and HAZ samples) were machined to dimensions of 10 mm length, 10 mm breadth and 8 mm thickness with lathe machine. They were mounted on thermosetting material known as Bakelite in order to make them convenient for handling. Thereafter, the surfaces of the specimens were then flattened by filing and grinding using laboratory grinding and polishing machines with a set of emery papers of 240, 320, 400, 600, 1000 and 1200 microns. The grinding was done in order of coarseness of the papers. As each specimen was changed from one emery papers to the other, it was turned through an angle of 90^o to remove the scratches sustained from the previous grinding. After grinding, the specimens were polished using rotary polishing machine, to give it mirror like surface, and in conformity with Bipin and Tewari, (2010) a polishing cloth was used to polish the surface of the specimens, the specimens were then etched in a solution of 1ml HCl+3ml HNO_3 +1ml glycerol and the microstructures examined at a magnification of 400xx using metallurgical microscope with camera attached. The microstructures of the as-received sample and HAZ samples at a range of welding variables were examined after etching in a solution of 1ml HCl + 3 ml HNO_3 + 1 ml glycerol using metallurgical microscope Model-Axio at magnification of 400xx.

Discussion of Results

The chemical composition shown in Table 1 confirmed that the as-received sample analyzed is Austenitic Stainless Steel since it has 8.079%, 18.403%, 0.038%, and 1.85% of Nickel, Chromium, Carbon and Manganese respectively. This was within the range of composition for Austenitic Stainless Steel (El-Batany, 1997).

Hardness characteristics of the as-received and HAZ samples at a range welding speeds (2.5–9.5 m/min) and power inputs are shown in Figures 2 and 3 respectively

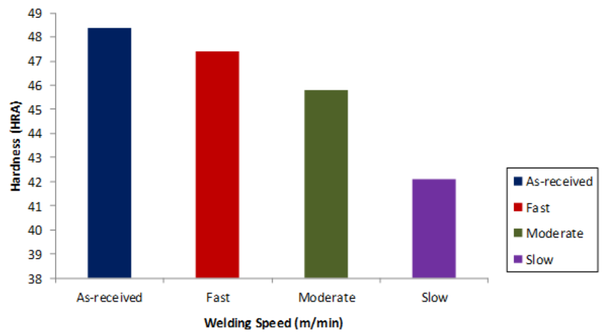

FIG. 2 VARIATION OF HARDNESS (HRA) WITH WELDING SPEEDS FOR HAZ SAMPLES AND AS-RECEIVED SAMPLE

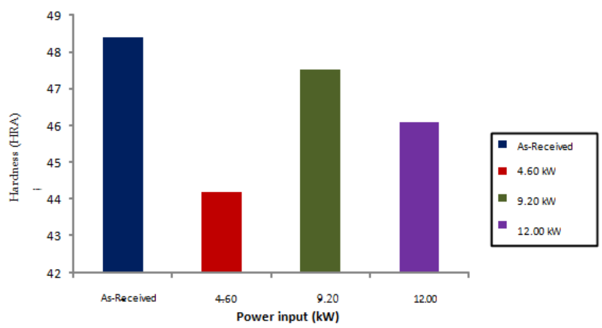

FIG. VARIATION OF HARDNESS (HRA) WITH POWER INPUTS FOR HAZ SAMPLES AND AS-RECEIVED SAMPLE

At all range of welding speeds, the observed inferior hardness characteristic of the HAZ relative to the received sample as depicted by Fig. 2 may be attributed to relative fine grain size of austenite and

ferrite phases of the as received sample. Previous studies have shown that welded materials are characterized by grain growth (Ramazan and Huseyin, 2002), therefore the superior hardness property of HAZ sample at fast speed as compared to moderate and slow speeds respectively may equally be explained by difference in grain size of the austenite and ferrite phases, and according to Lothongkum, et al., (2001), due to fast cooling rate resulting from low heat input, the weld freezes quickly with concomitant small grains. Also, Sathiya et al., (2004), in their investigation on friction welding of austenitic stainless steel and optimization of weld quality have equally attributed increase in hardness at the joint zone to grain refinement.

The obtained hardness characteristic of the HAZ sample in order of 9.20 KW, 4.60 KW and 12.0 KW power input (Fig. 3), may have resulted from relative grain growth as well, according to EL-Batahgy and Abdel- Monem, (1997), slow cooling due to increasing power inputs results in coarser dendritic structures and Afolabi, (2008), attributed the relative coarse grains of HAZ samples with increasing power input to slow cooling rate resulting from high heat input. Other factors which may have contributed to the observed hardness characteristics of the HAZ samples include greater reformation of austenite and plastic deformation caused by multi-pass welding (Fowless et al., 2008).

Also, the obtained low hardness property of the HAZ samples at the range of power inputs relative to the received sample may be accounted for by change in ferrite number (FN) at the root during thermal cycling (Fowless and Blake, 2008).

Microstructures

Results of microstructural examinations for the as-received sample is shown in Plate 1, and HAZ samples at a range of welding speeds and power inputs are depicted in Plates 2(a-c) and 3(a-c) respectively.

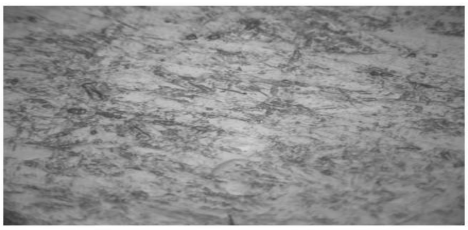

PLATE 1 MICROGRAPH OF AS – RECEIVED SAMPLE AFTER ETCHING IN SOLUTION OF 1 ml HCl + 3 ml HNO_3 + 1ml GLYCEROL AT MAGNIFICATION OF 400xx, SHOWING FERRITE PHASE (LIGHT PORTION) IN THE MATRIX OF AUSTENITE PHASE (DARK PORTION).

PLATE 2(a-c) MICROGRAPHS OF HAZ SAMPLES AT SLOW, MODERATE AND FAST SPEEDS RESPECTIVELY AFTER ETCHING IN SOLUTION OF 1 ml HCL + 3 ml HNO_3 + 1ml GLECEROL AT MAG. 400xx. SHOWING VARIED VOLUME FRACTION OF FERRITE PHASE (LIGHT PORTION) IN THE MATRIX OF AUSTENITE PHASE (DARK PORTION) WITH SOME CHROMIUM PRECIPITATES (WHITE PATCHES) AND POROSITIES (DARK DOTS) WITHIN THE MICROSTRUCTURE

The obtained microstructural features of the as-received sample shown in plate 1 may have resulted from pre-history of the sample, that is, the initial treatment(s) the sample was subjected to prior welding, while those of the HAZ samples given in plates 2(a-c) and 3(a-c), may have be influenced majorly by the conditions (varied range of welding speed and power input). Mortensen et al., (2000), have showed that slow cooling due to low welding speed and high heat input promotes a greater reformation of austenite, a condition which they said is beneficial, and an increase in the ferrite grain size, a condition which they said is non- beneficial. Also, Ramazan and Huseyin, (2002), in their investigation on the mechanical properties of austenitic stainless steels

welded by GMAW and GTAW revealed that fast cooling rates depress the reformation of austenite, resulting in higher level of retained ferrite, a situation which they said adversely affects ductility, toughness and corrosion resistance. Hence, to optimize the crystal structure within the HAZ, a critical balance between these two extremes must be attained. Therefore, the obtained relative improved hardness characteristic of the HAZ sample at fast welding speed and power input of 9.20 KW is attributed to relative balanced austenite and ferrite phases in the samples' microstructure at different ranges of welding speeds and power inputs.

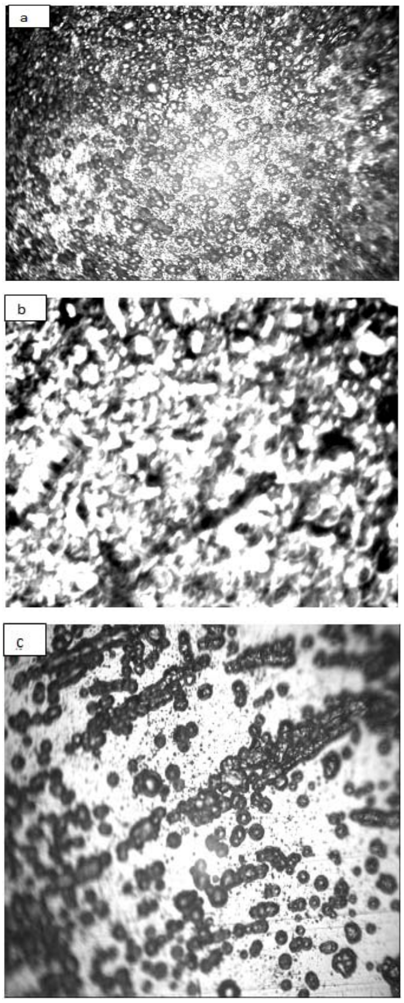

PLATE 3(a-c) MICROGRAPHS OF HAZ SAMPLES AT 4.60 kW, 9.20 kW AND12.00 kW POWER INPUTS RESPECTIVELY AFTER ETCHING IN SOLUTION OF 1ml HCL+3 ml HNO_3+1ml GLECEROL AT MAG. 400xx. SHOWING VARIED VOLUME FRACTION OF FERRITE PHASE (LIGHT PORTION) IN THE MATRIX OF AUSTENITE PHASE (DARK PORTION) WITH SOME CHROMIUM PRECIPITATES (WHITE PATCHES) AND POROSITIES (DARK DOTS) WITHIN THE MICROSTRUCTURE.

In addition, ratio of Cr_{eq}/Ni_{eq} in the HAZ region of the weld metal may also have contributed to the obtained microstructural features. According to Ramazan and Huseyin, (2002), when Cr_{eq}/Ni_{eq} ratio is lower than 1.5, more volume fraction of austenite phase is formed with about 2 or 3 volume % ferrite. This volume % range is required in the weld metal to reduce trend of crack susceptibility, which is due to more residual elements that spoil pureness can be easily solute in ferrite. Based on Schaeffler equivalent equation, the calculated Cr_{eq}/Ni_{eq} ratio was 1.9 in this study as compared to the 1.5 proposed, hence more than 2 or 3 vol. % ferrite is expected to be present in the HAZ microstructures, and according to Gunaraj et al., (2002), the existence of a few percent of ferrite is useful to remove the tensile stress thereby preventing risk of microcracking during solidification. Therefore, the observed variations in hardness characteristics of the HAZ sample under varied welding speed and power input may be due to relative absence of micro cracks. Furthermore, the chromium carbide (white patches) formation and precipitation due to sensitization at the grain boundaries in the HAZ when heated in the 800 to 1600^0F (427 to 871^0C) may have influenced hardness behaviour of the HAZ sample, and according to Afolabi, (2008), the higher the carbon level of the material welded is, the greater the likelihood that the welding thermal cycle will result in chromium carbide precipitation is, which is detrimental to both corrosion and mechanical properties.

Also, the observed differently featured HAZ microstructures could be largely due to effects of thermal cycling (Bipin and Tewari, 2010). Hence, the observed varied hardness characteristics may be due to relative volume fraction of phases formed under the varied welding speed and power input.

Conclusions

The following conclusions were drawn from the work:

a) Variation in volume fraction and grain size of austenite was observed in all the HAZ microstructures examined. In addition, chromium carbide formation and precipitation due to sensitization was observed at the grain boundaries, in addition, ferrite phase was equally seen to be present in all the microstructures examined, also observed in the microstructures of HAZ sample were inclusions in form of dark spots.

b) Optimum hardness was obtained at fast welding speed of 9.5 m/min and 9.20 kW power input.

c) The as-received sample was found to reveal superior hardness over the HAZ samples at a range of welding speeds and power inputs.

Recommendations

(i) Effects of other crucial welding variables (welding electrode, weld geometry, polarity, electrode diameter, arc voltage, electrode extension, electrode angle and flux depth) should be investigated.

(ii) Tensile strength and impact toughness of the material under a range of welding speeds and power inputs should also be studied.

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